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ABSTRACT

Understanding the primary causes of indoor air quality (IAQ) problems and how controllable factors--proper heating, ventilation and air-conditioning (HVAC) system design, allocation of adequate outdoor air, proper filtration, effective humidity control, and routine maintenance--can avert problems may help all building owners, operators, and occupants to be more productive. This revised report provides a comprehensive summary of IAQ research that has been conducted in various types of facilities. It focuses primarily on school facilities because, for numerous reasons, they are far more susceptible to developing IAQ problems than most other types of facilities, and the occupants--children--are more significantly affected than adults are. This revised report contains summaries of more recent IAQ articles, with 50 new items added to the references. In addition, it expands the discussion of carbon dioxide in response to concerns about this section in the first version of the report. (Contains 154 references.) (EV)

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ED 464 475

# Causes of Indoor Air Quality Problems in Schools

## Summary of Scientific Research

### Revised Edition

*Prepared by*
*the Energy Division*
*Oak Ridge National Laboratory*
*for the*
*U.S. Department of Energy*

ornl

**Charlene W. Bayer**
**Sidney A. Crow**
**John Fischer**

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*May 2000*

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# Causes of Indoor Air Quality Problems in Schools

## Summary of Scientific Research

### Revised Edition

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## ❖ PREFACE TO REVISED EDITION

Since this report was first published, a number of new articles reporting the results of research on IAQ in schools have appeared in journals and conference proceedings. Several of these articles deal with the impact of indoor airborne contaminants on students' health. As a result of this additional research, particularly the health-related papers, we decided to update and revise this literature review summary report. The text of this revised report contains summaries of these recent IAQ articles, with 50 new items added to the References. In addition, we have expanded the discussion of carbon dioxide in response to concerns about this section in the first version of the report.

## ❖ ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| cfm | cubic feet per minute |
| cfu | colony-forming unit |
| CO | carbon monoxide |
| $CO_2$ | carbon dioxide |
| DWERS | dual-wheel total energy recovery system |
| ERV | energy recovery ventilator |
| HVAC | heating, ventilation, and air-conditioning |
| IAQ | indoor air quality |
| MVOC | microbial volatile organic compound |
| $NO_2$ | nitrogen dioxide |
| $NO_x$ | oxides of nitrogen |
| $PM_{10}$ | particulate matter of <10 $\mu$m diameter |
| $PM_{2.5}$ | particulate matter of <2.5 $\mu$m diameter |
| ppm | parts per million |
| RH | relative humidity |
| SBS | sick building syndrome |
| TERS | single-wheel total energy recovery system |
| VAV | variable air volume |
| VOC | volatile organic compound |

## 1 ❖ School Facilities and Indoor Air Quality

According to the U.S. government's General Accounting Office, one in five schools in the United States—representing 8.4 million students—has problems with indoor air quality (IAQ) (GAO 1995, 1996). According to the same studies, 36% of the schools surveyed listed HVAC systems as a "less-than-adequate building feature." The reports also suggested that there appears to be a correlation between unsatisfactory IAQ and the proportion of a school's students coming from low-income households.

Fourteen states regulate one or more environmental factors related to IAQ in schools (ELI 1996). These regulations and states include

- pesticide application: Arizona, Louisiana, Michigan, Montana, Tennessee, and Texas;
- urea-formaldehyde insulation: California and Connecticut;
- ventilation standards in schools, public buildings, or workplaces: California, Connecticut, Maine, New Jersey, and New Hampshire;
- mandatory consideration of IAQ in school energy conservation efforts: California and Maine;
- state review or evaluation of school IAQ: Florida, Maine, and New Hampshire;
- state assistance to local health departments in adopting IAQ programs in public buildings: Wisconsin;
- mandatory school IAQ programs and best practices requirements to improve IAQ in new school buildings: Washington.

*One in five U.S. schools have indoor air quality (IAQ) problems, a real concern in schools because*

- *children are still developing physically and are more greatly affected by pollutants;*
- *the number of children with asthma is up 49% since 1982;*
- *children up to the age of 10 have three times as many colds as adults;*
- *poor IAQ can lead to drowsiness, headaches, and a lack of concentration.*

Most other states are less proactive and are therefore dependent upon national building standards such as the Southern Building Code, industry standards such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers

(ASHRAE) Standard 62-1989, and the professional judgment of architects, consulting engineers, and state and local school facility managers. These decision makers are faced with many priorities other than IAQ concerns, all of which compete for what is often a limited budget.

Bascom (1997) states that "schools are facing two epidemics: an epidemic of deteriorating facilities and an epidemic of asthma among children." He notes that while clinicians are trying to instruct schools regarding environmental control measures for children with asthma, these clinicians have little information about the conditions and practical means in schools. The schools are ill-equipped to receive the recommendations, assess their reasonableness, and effect the recommendations at a reasonable cost. Bascom calls for the development of task forces to assemble the necessary expertise to solve these problems. He points to the need for a controlled IAQ research study so that effective IAQ plans can be developed and implemented.

There are many reasons to consider IAQ a top priority in the school environment. One is that children are still developing physically and are more likely to suffer the consequences of indoor pollutants. Another is that the number of children suffering from asthma is up 49% since 1982, according to the American Lung Association (Sundell and Lindvall 1993). Asthma is the principal cause of school absences, accounting for 20% of lost school days in elementary and high schools (Richards 1986). Richards also notes that allergic disease (nasal allergy, asthma, and other allergies) is the "number one" chronic childhood illness, accounting for one-third of all chronic conditions occurring annually and affecting 20% of school children. Children from birth to age 10 have three times as many colds as adults (Tyrrell 1965, p. 19). School facilities, by design, are densely populated, making the task of maintaining an acceptable IAQ more difficult than in many other types of facilities. Another consideration is that the sole purpose of a school facility is to foster the learning process, which is impacted directly by the quality of the indoor environment (HPAC 1990; Dozier 1992; Boone et al. 1997). Finally, most individuals have experienced drowsiness, lack of concentration, or headaches in a classroom or auditorium environment and understand the impact these symptoms have on comprehension and motivation. ❖

## 2 ❖ BACKGROUND

In the modern urban setting, most individuals spend about 80% of their time indoors and are therefore exposed to the indoor environment to a much greater extent than to the outdoors (Lebowitz 1992). Concomitant with this increased habitation in urban buildings, there have been numerous reports of adverse health effects related to IAQ ("sick buildings"). Most of these buildings were built in the last two decades and were constructed to be energy-efficient.

The quality of air in the indoor environment can be altered by a number of factors: release of volatile compounds from furnishings, floor and wall coverings, and other finishing materials or machinery; inadequate ventilation; poor temperature and humidity control; re-entrainment of outdoor volatile organic compounds (VOCs); and the contamination of the indoor environment by microbes (particularly fungi). Armstrong Laboratory (1992) found that the three most frequent causes of IAQ are (1) inadequate design and/or maintenance of the heating, ventilation, and air-conditioning (HVAC) system, (2) a shortage of fresh air, and (3) lack of humidity control. A similar study by the National Institute for Occupational Safety and Health (NIOSH 1989) recognized inadequate ventilation as the most frequent source of IAQ problems in the work environment (52% of the time).

*A study by Armstrong Laboratory, at Brooks Air Force Base, Texas, found that the three most frequent causes of unacceptable indoor air quality (IAQ) are (1) inadequate design and/or maintenance of the heating, ventilation, and air-conditioning (HVAC) system, (2) a shortage of fresh air, and (3) lack of humidity control.*

Poor IAQ due to microbial contamination can be the result of the complex interactions of physical, chemical, and biological factors. Harmful fungal populations, once established in the HVAC system or occupied space of a modern building, may episodically produce or intensify what is known as sick building syndrome (SBS) (Cummings and Withers 1998). Indeed, SBS caused by fungi may be more enduring and recalcitrant to treatment than SBS from multiple chemical exposures (Andrae 1988). An understanding of the microbial ecology of the indoor environment is crucial to ultimately resolving many IAQ problems. The incidence of

SBS related to multiple chemical sensitivity versus bioaerosols (aerosolized microbes), or the contribution of the microorganisms to the chemical sensitivities, is not yet understood.

If the inhabitants of a building exhibit similar symptoms of a clearly defined disease with a nature and time of onset that can be related to building occupancy, the disease is generally referred to as "building-related illness." Once the SBS has been allowed to elevate to this level, buildings are typically evacuated and the costs associated with disruption of the building occupants, identification of the source of the problem, and eventual remediation can be significant.

Understanding the primary causes of IAQ problems and how controllable factors—proper HVAC system design, allocation of adequate outdoor air, proper filtration, effective humidity control, and routine maintenance—can avert the problems may help all building owners, operators, and occupants to be more productive (Arens and Baughman 1996). This report provides a comprehensive summary of IAQ research that has been conducted in various types of facilities. However, it focuses primarily on school facilities because, for numerous reasons that will become evident, they are far more susceptible to developing IAQ problems than most other types of facilities; and the occupants, children, are more significantly affected than adults (EPA 1998). ❖

## 3 ❖ IAQ Investigations Conducted in School Facilities

Daisey and Angell (1998) conducted a survey and critical review of the existing published literature and reports on IAQ, ventilation, and building-related health problems in schools. They found that the types of health symptoms reported in schools are very similar to those defined as SBS, although this finding may be due, at least in part, to the type of health symptom questionnaires used. Some of the symptoms (e.g., wheezing) are indicative of asthma. In the studies in which "complaint" and "noncomplaint" buildings were compared, complaint buildings usually had a higher rate of health-related symptoms.[1]

Formaldehyde, total VOCs, $CO_2$, and bioaerosols were the most commonly measured pollutants in schools. Most of the formaldehyde measurements made in the United States were in complaint schools but were still generally below 0.05 ppm. The measurements of the other pollutants were too limited to draw conclusions as to the prevalence of indoor concentrations of concern, even in problem schools. However, there was some evidence that microbiological pollutants are of particular concern. The few scientific studies on causes of symptoms in complaint schools indicate that exposure to molds and allergens in schools contributes to asthma, SBS, and other respiratory symptoms. Other indoor pollutants, such as VOCs and aldehydes, have been investigated to only a very limited extent, although there are reasons to suspect that they may also contribute to the prevalence of health-related symptoms in schools.

The major building-related problem identified was inadequate outdoor air ventilation. Water damage to the building shells of schools, leading in turn to mold contamination and growth, was the second most frequently reported building-related problem. The root cause of many of the ventilation and water-damage problems in the schools was inadequate and/or deferred maintenance of school buildings and HVAC systems.

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1. Complaint buildings are those for which an abnormal number of complaints are made regarding the quality of the indoor air.

Daisey and Angell concluded that there is now considerable qualitative information on health complaints, ventilation, and IAQ problems in complaint schools. It is unknown what fraction of schools are experiencing IAQ and ventilation problems and related health problems. There is also a lack of the scientifically rigorous and quantitative information on causal relationships between health symptoms, exposure, and dose-response relationships that is needed to establish health standards for the protection of children in schools. The effectiveness and the costs and benefits of various remedial actions undertaken to solve problems in specific schools remain largely unknown.

*Daisey and Angell found that the major building-related problems in "complaint" schools were inadequate outdoor ventilation, followed by water damage to building shells that set up conditions for mold contamination and growth.*

The report recommended the following research:

- Determine more quantitatively the degree to which IAQ problems in schools increase asthma, SBS symptoms, and absentee rates of students.
- Identify the specific agents that cause health effects and determine exposure- and dose-response relationships for those pollutants that are the most significantly related to health symptoms.
- Determine whether learning can be significantly increased through improved IAQ.
- Determine the cost-effectiveness of various remediation measures undertaken to solve problems in complaint schools through intervention studies in which changes in health symptoms and test scores are measured before and after remediation.
- Determine the costs of deferred building maintenance with respect to health and learning in students.
- Determine the viability of using $CO_2$ detectors and other types of sensors to routinely control ventilation and to provide an indication of inadequate ventilation.
- Develop improved sampling and analysis methods for bioaerosols.
- Develop low-cost samplers for measuring 6-hour exposures to other key indoor pollutants, such as aldehydes, that may be contributing to the kinds of symptoms observed in problem schools.

The U.S. Environmental Protection Agency (EPA 1998) is formulating a major study of IAQ in school buildings to provide baseline IAQ data. The study is to be similar to the BASE study (Womble et al. 1993) on office buildings, following a similar protocol. Six basic activities have been proposed:

- school selection representing both public and private schools;
- physical characterization of the buildings in terms of location, physical structure, ventilation, occupant density, occupant activities, and potential indoor pollutant sources associated with special use areas;
- definition of building study areas and random selection of four study areas for more extensive evaluation;
- monitoring for one week in the study areas to generate data on HVAC operation, environmental problems, and comfort factors using standard procedures and good quality assurance/quality control practices;
- administration of an occupant questionnaire to all adult occupants; and
- development of a publicly accessible database of study results.

Parameters proposed for monitoring include

- temperature, relative humidity, sound level, and illuminance;
- air pollutants [$CO_2$, CO, inhalable particles ($PM_{2.5}$ and $PM_{10}$), VOCs, formaldehyde, bioaerosols, radon];
- HVAC supply measurements (airflow rate, air temperature, air relative humidity);
- percentage and rate of outdoor air intake;
- exhaust fan and supply diffuser airflow rates; and
- supply diffuser parameters (temperature, relative humidity, and $CO_2$).

The protocol is currently in a draft form and is not to be cited or quoted specifically.

Henckel and Angell (1999) reported on the results of 169 investigative reports of IAQ in Minnesota schools. Data were collected on health and environmental complaints, pollutant concentrations, and building-related factors. Health complaints, particularly upper respiratory and central nervous system problems, occurred at a frequency similar to that of environmental complaints. The majority of environmental complaints were about odors, too little air movement, and temperature variation. Carbon dioxide levels were elevated in 66% of the schools in which measurements were taken. Microbiological contamination was the primary concern in 33% of the investigations. The most commonly cited building factor associated with IAQ complaints was insufficient outdoor air supply; moisture problems were ranked second, and poor air distribution was ranked third. Henckel and Angell concluded that a significant number of IAQ problems could be avoided by addressing ventilation and moisture problems.

Downing and Bayer (1993) investigated the relationship between ventilation rate and IAQ in classrooms. Samples were collected and analyzed for VOCs, formaldehyde, $CO_2$, temperature, and humidity. Downing and Bayer confirmed in

this study that 15 cfm per student of outdoor air was required to maintain $CO_2$ concentrations at levels below 1000 ppm. The recommendation was made that classrooms, both new and existing, be provided with at least 15 cfm per student of outdoor air on a continuous basis during school hours. It was found that VOC concentrations exceeded 1000 $\mu g/m^3$ when only 5 cfm per student was provided, even on a continuous basis. Tucker (1986) indicated that this level of VOCs is an indication of potential IAQ problems.

Downing and Bayer also measured space humidity as a function of the operating mode of packaged rooftop equipment compared with humidity levels maintained with a system utilizing a dual-wheel total energy recovery system (DWERS) (see Fig. 1). Humidity measurements collected over time for a school that had experienced serious microbial and IAQ problems showed that even with only 5 cfm per student being provided on a continuous basis, the space relative humidity exceeded 80% for an extended period of time and averaged well over 70% during the investigation. When the fan was cycled with the cooling coil, the average space humidity dropped somewhat to approximately 70%, but it still exceeded 80% during the evening hours. With the DWERS maintaining the humidity content of the continuously supplied outdoor air, the space relative humidity averaged 53% and remained below 58% throughout the investigation.

*In a school studied by Downing and Bayer, there was visible mold on building surfaces before retrofit. With a DWERS installed, average relative humidity dropped from 80% to 53%.*

Downing and Bayer reported that before the school was retrofitted with a DWERS, there was visible mold growth on building surfaces, carpeting, and books. The IAQ complaints and illnesses included respiratory and allergy problems, headaches, and lethargy. The HVAC system modification, which provided increased outdoor air quantities on a continuous basis while controlling space humidity, eliminated both the mold and the IAQ complaints by the teachers and students. This finding was confirmed through follow-up interviews by Downing and Bayer with a number of the teachers who had complained the most about the building's IAQ prior to the HVAC system retrofit.

Bayer, Crow, and Noble (1995) reported on case studies conducted in five school systems in Georgia. In each of these schools, the students and teachers were experiencing rashes and respiratory illnesses. In each of the schools, microbial amplification was identified, and *Cladosporium* sp. was the most prevalent fungi found. Although atopic dermatitis has been reported to be relatively rare, one cause may be contact with molds such as *Alternaria*, *Cladosporium*, and *Aspergillus* in atopic individuals (Flannigan and Morey 1996). Bayer, Crow, and Noble also

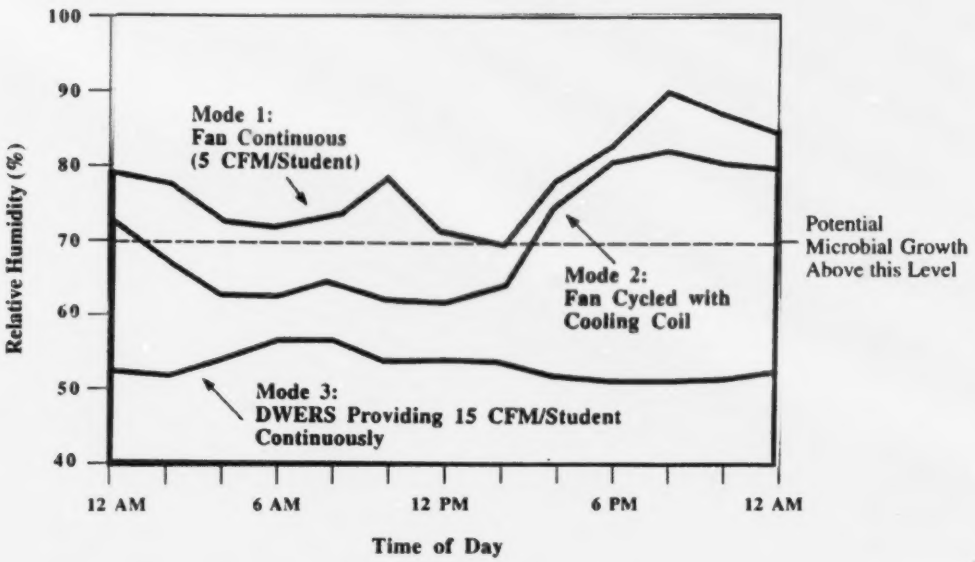


**Fig. 1. Space humidity measured by Downing at three operating modes with and without the dual-wheel total energy recovery systems, showing lack of humidity control with conventional packaged HVAC units.**

confirmed, via comparison of field results with laboratory studies, that many of the detected VOCs were microbial in origin.

Bayer (unpublished results) investigated IAQ problems in a southern school that had had to conduct an emergency evacuation because of strong odors and visible microbial growth. The school had to be abandoned within a few weeks after completion of a massive renovation that included new rooftop HVAC units, new carpeting, furnishings, painting, and so on. The carpet was covered with visible microbial growth and had a strong cinnamon odor in the most contaminated areas. Investigation revealed that water was condensing under the carpet on the concrete slab as a result of the poor humidity control within the building. Using environmental chamber technology to simulate ongoing conditions in the school, Bayer found that the carpet adhesive would reactivate to a wet state whenever it was exposed to humidities greater than 75% for a period of several hours. The adhesive would reset to a hardened state when the humidity was lowered below 75% for several hours. When the adhesive was wet, strong solvent-type odors were emitted. The biocide present in the adhesive was designed to prevent microbial growth only in the sealed container before use; it was not able to prevent microbial growth in this cycling wet-dry-wet state. Without biocide protection, the carpet adhesive was an excellent nutrient base for microbial growth. The result was excessive amounts of microbial growth. The volatile emissions from the microbes

were very strong: total VOC levels in the school exceeded 23,000 $\mu g/m^3$. The hexane levels exceeded 13,000 $\mu g/m^3$.

Although schools are prime candidates for fungal colonization, few studies have systematically examined the mycoflora of school buildings. Crow et al. (1993, 1994); Crow, Ahearn, and Noble (1995); Bayer and Crow (1992); Bayer, Crow, and Noble (1995); and Downing and Bayer (1993) have examined a number of buildings, including primary and secondary schools and university buildings. Samples represent a single collection of airborne viable samples from sites of amplification where fungal colonies were growing on surfaces within the building.

Crow et al. (1994) reported on two schools in a series of ten buildings sampled for airborne fungi. Both schools had both complaint and control sites. The first school had humidities of 58–61% during the test period. The viable fungal counts were 140–1615 cfu/$m^3$. Populations were dominated by species of *Cladosporium* and *Penicillium*. The second school had relative humidities of approximately 60–63% during the test period. This school had experienced obvious humidity control problems, indicated by sagging ceiling tiles and evidence of water condensation; and it yielded extremely high fungi numbers (735–5180 cfu/$m^3$) found on a variety of media. The dominant species were again *Cladosporium* and *Penicillium*.

In a second paper Crow, Ahearn, and Noble (1995) discussed three additional schools. The viable counts of airborne fungi were lower (35–1280 cfu/$m^3$) than those described for the previous schools. Dominant species were *Cladosporium* and *Penicillium*. At three additional schools sampled (unpublished data), airborne counts were in similar ranges and were generally dominated by *Cladosporium* and *Penicillium*. Clearly, variations in seasonal occurrence of outdoor fungi can confuse the interpretation of indoor air counts. Critical seasonal studies coupled with sophisticated data on humidity and the nature of volatiles will help clarify the meaning of airborne viable counts. Understanding of the basic physiological phenomena in microbes and the influence of environmental parameters on variation in basic processes, such as the formation of conidia and volatiles and their subsequent release, will clarify the etiology of SBS.

Wurtz et al. (1999) investigated airborne microflora in four schools in Denmark. Thirty percent of the samples taken in this study contained bacteria concentrations of more than $5.0 \times 10^3$ cfu/$m^3$, which may indicate crowding or poor ventilation. These researchers found that significant parameters for predicting airborne bacterial concentrations were air exchange rate and the area (in cubic meters) per person. Area per person also appeared to be associated with airborne fungal concentrations.

Bartlett, Kennedy, and Brauer (1998, 1999a,b) recently conducted one of the few statistically significant IAQ investigations of schools. These researchers investigated IAQ in terms of microbial contamination (focusing on mesophilic and thermophilic fungi and bacteria), occupancy load and patterns, $CO_2$, total particles, temperature, humidity, and air change rates in 39 schools in British Columbia, a coastal and temperate climate zone. The 39 noncomplaint schools were randomized into three identifiable sampling periods—winter, spring, and fall. Two sampling cycles were required to investigate all of the schools, with three rooms sampled in each school. Bartlett, Kennedy, and Brauer found that the outdoor concentration of mesophilic fungi was statistically different from the indoor concentration and that the variable with the highest predictive value for indoor mesophilic fungi was outdoor temperature (using multiple linear regression equations, $r^2 = 0.61$). There was a seasonal correlation with concentrations of the fungi, and the winter indoor and outdoor counts were lower than either the spring or fall counts. Twenty-eight percent of the classrooms studied had culturable fungal concentrations greater than 500 cfu/$m^3$. The xerophilic fungi (those able to grow with reduced biologically available water) were present in greater concentrations in the fall. Xerophilic fungi are potential colonizers of building materials and potential allergens. Some xerophilic genera are suspected of being contributors to fungal allergic responses.

The apparent failure, found by Bartlett, Kennedy, and Brauer, of school ventilation systems to filter out fungi originating from the outside could allow for increased fungal exposure to susceptible individuals. Seventy-one percent of the classrooms failed to meet the ASHRAE 62-1989 ventilation standard. Forty-five percent of the classrooms had average $CO_2$ concentrations greater than 1000 ppm. Using multiple linear regression equations, these authors found that the highest predictive value for bacterial concentration was indoor $CO_2$ concentration ($r^2 = 0.586$), and concluded that high commensal bacterial counts were related to inadequate ventilation of the occupied spaces. The air exchange rates were lower in winter, when the HVAC systems were set at the minimum outside air supply level by the school facilities managers to reduce energy usage or avoid dumping cold air on the space occupants. The mean relative humidity level during the winter season was 36.9%. Bartlett, Kennedy, and Brauer concluded that the combination of the lower relative humidity and the inefficient ventilation, particularly in the winter season, may contribute to the spread of airborne infectious diseases that are common in classroom settings.

*In Canadian schools studied by Bartlett, Kennedy, and Brauer, 71% of the classrooms failed to meet the ASHRAE ventilation standard, and 45% of the classrooms had average $CO_2$ concentrations above the ASHRAE maximum limit of 1000 ppm.*

In a 1998 paper, Lytton stated: "It is often taken for granted that schools are incubators of disease. . . . Most of us probably grew up assuming that schools are places where illnesses spread from child to child and from children to staff" (Lytton 1998). Unfortunately, in most schools this is true, but with better control and understanding of school indoor environments this is not an inevitable situation. Disease and allergenic agents are airborne particles that are spread among building occupants. These particles are droplet nuclei (ranging in size from 1 to 5 $\mu$m) and fungal spores (ranging in size from 1 to 5 $\mu$m)—particles that can be removed from air by commercially available filters (Wheeler 1993).

Green (1985) reduced airborne bacteria levels in school classrooms by filtering recirculated air. He reported that in the studied school, respiratory infection accounted for 60% of all absenteeism prior to reduction of the airborne bacteria levels through filtration. Wheeler (1993) applied the Wells-Riley equation to predict the performance of alternative air-conditioning systems, dilution ventilation rates, and filter efficiencies for calculation of risk of infection in an elementary school classroom. Wheeler's modeling technique can be applied to calculate the filtration efficiencies and HVAC system performance needed to reduce the risk of infections among school children, teachers, and staff.

Mouilleseaux, Squinazi, and Festy (1993) conducted a microbial characterization of the indoor air in the classrooms in ten primary and nursery schools in Paris. The average aerobic bacteria count was 3000 cfu/m$^3$. They found that 32.7% of the analyzed samples contained *Staphylococcus aureus* (a germ indicative of human mucous/cutaneous contamination), 6.2% contained enterobacteria (a marker of faecal/hydrotelluric air contamination), and 50.6% contained thermotolerant *Streptococcus* (a marker of faecal/hydrotelluric air contamination). The average fungal counts were 100 cfu/m$^3$, and yeasts were 20 cfu/m$^3$. The fungal flora were polymorphic.

Airborne microbial contamination in naturally and mechanically ventilated buildings was studied by Maroni et al. (1993). These buildings included ten schools and seven office buildings. Maroni et al. did not find major differences in detected fungi between naturally and mechanically ventilated buildings. However, in the mechanically ventilated buildings, they did find a significant correlation between microorganisms and the relative humidity in wintertime, a negative correlation between bacteria and particulate matter in summertime, and a positive correlation between bacteria and temperature in summertime. They also found a weak correlation between total VOCs and fungi in the schools.

Rand (1999) inspected 631 schools in the Canadian Atlantic provinces for mold contamination. He found that species type and amounts vary widely depending on

the school construction type, school age, and composition and water activity of the amplifying substrate material. The most common contamination sites, in descending order of occurrence, are classrooms and administration sites, especially in peripheral wall cavities and ceiling plenums; libraries; gymnasiums; basements and crawl spaces; ventilation systems; janitor and mechanical rooms; and portable classrooms. The most commonly contaminated substrates in schools are drywall, ceiling tiles, structural wood, insulation, carpets, and concrete wall surfaces that have been exposed to chronic water infiltration, condensation, and/or wicking problems. Mold species composition in normal and moisture-damaged schools vary greatly. Species commonly encountered in moisture-damaged schools are *Acremonium* spp., *Aspergillus fumigatus, Aspergillus niger, Aspergillus ustus, Aspergillus versicolor, Chaetomium* spp., *Paecilomyces variotii, Penicillium brevicompactum, Penicillium aurantiogriseum complex, Penicillium variablile, Phoma* spp., *Stachybotrys chartarum, Trichoderma harzianum,* and *Tichoderma viride*. In schools not damaged by moisture, the mold species assemblage should be similar to that encountered in the surrounding outdoor environment. An understanding of the school building design is required to identify and remediate amplification sites. Rand found a positive correlation between health complaints and the presence of certain toxigenic molds (*Penicillium aurantiogriseum* and *Trichoderma harzianum*) in the studied schools.

*In one study of more than 600 school children, although skin tests showed low sensitivity to common molds and allergens, reactivity to molds appeared to be associated with asthma or asthma-like symptoms.*

The sensitization of 622 school children to molds and respiratory symptoms was investigated by Taskinen et al. (1999). Two elementary schools were targeted for this research—one with a documented moisture problem (the index school) and one without a moisture problem (the control school). The geometric mean of total viable fungi concentration was 21 cfu/$m^3$ in the index school and 4 cfu/$m^3$ in the control school. In the index school, the primary species isolated from the indoor air and/or building materials were *Aspergillus fumigatus, Aspergillus versicolor, Actinomycetes, Eurotium, Exophiala, Fusarium, Phialophora, Rhodotorula, Stachybotrys, Trichoderma,* and *Wallemia*. Low indoor air concentrations of *Aspergillus fumigatus, Actinomycetes, Eurotium,* and *Wallemia* were found in the control school. Taskinen and associates distributed a questionnaire to children ranging in ages between 7 and 13; in addition, the children received skin prick tests for 13 molds and 11 common allergens. The researchers found that although skin test positivity was rare in the children (only 2% had strong positive tests), reactivity to molds appeared to be associated with asthma or asthma-like symptoms. Respiratory

infections seemed to be associated with mold exposure. Asthma and asthma-like symptoms were common in the children from the index school.

Thorstensen et al. (1990) studied ten schools in Greater Copenhagen to quantify pollutant sources in the schools and to relate students' complaints and symptoms to physical, chemical, biological, and sensory measurements. The IAQ in the schools was investigated under three conditions: (1) while the schools were unoccupied and the mechanical ventilation system was not operating (if the school was mechanically ventilated; six of the ten schools were mechanically ventilated); (2) while the schools were unoccupied and the mechanical ventilation system (if available) was operating; and (3) while the schools were normally occupied and ventilated. A panel of students trained in making sensory measurements by the "olf" method (Fanger 1988) determined the quality of the air. Ventilation rate, $CO_2$, airborne bacteria and microfungi, airborne dust, accumulated floor dust, immunogenic components in floor dust, total volatile organic compounds, temperature, and relative humidity were measured. Thorstensen et al. found considerable variation between the schools, especially in prevalence of students' symptoms, physical and sensory measurements, and pollutant loads. They found a significant correlation between the panel's decipol judgment of air quality and the prevalence of symptoms. On average the ventilation rate was only 2.3 L/s per olf in the six mechanically ventilated schools, approximately three times lower than the recommended 7 L/s per olf level (Fanger 1988). In the mechanically ventilated schools, the pollutant source determinations indicated that 40% were a result of the ventilation system, 40% were from the occupants, and 20% were from other sources.

Smedje, Norback, and Edling (1997) studied the perceptions of school occupants of the IAQ in their schools. Data on subjective air quality, domestic exposures, and health aspects were gathered via questionnaires sent to all school employees in 38 schools (1410 people in all) in Sweden. Exposure data were gathered by classroom monitoring of temperature, relative humidity, rate of air exchange, $CO_2$, CO, $NO_2$, formaldehyde, other VOCs, respirable dust, molds, bacteria, settled dust, and mite allergens. The questionnaires indicated that 53% of the school occupants perceived the IAQ in their school as bad or very bad. The younger staff were more dissatisfied than older personnel. Also, those from homes with no tobacco smoking were less tolerant of the school indoor environment. Dissatisfaction also was increased among those dissatisfied with their psychosocial work climate. In older school buildings and buildings with displacement ventilation, there was less dissatisfaction with the IAQ.

Smedje, Norback, and Edling demonstrated that the subjective perceptions of air quality were related significantly to exposure to microorganisms, VOCs, and dust, as well as to personal factors such as age, atopic disposition, and perceived work

social climate. Respondents with allergies or an atopic disposition were more negative about school IAQ. Significant correlations were found between subjective air quality and exposure to settled and airborne dust, mold and bacteria, and total volatile organic compounds. Even at low concentrations, these pollutants affected perceived IAQ.

Smedje, Norback, and Edling did not find a significant relationship between the complaints and the rate of air exchange or the $CO_2$ concentration. The $CO_2$ levels ranged from 375 to 2800 ppm. The air quality was perceived to be worse at higher exposure levels of airborne contaminants, such as VOCs (which ranged between 3 and 580 $\mu g/m^3$), molds (ranging between 7 and 360 $\times$ $10^3/m^3$ for total molds), bacteria (ranging between 8 and 290 $\times$ $10^3/m^3$ for total bacteria), $NO_2$ (ranging between 1 and 11 $\mu g/m^3$), CO (ranging between <0.1 and 0.9 $\mu g/m^3$), and respirable dust (ranging between 6 and 60 $\mu g/m^3$). Therefore, they concluded that exposure to indoor pollutants affects the perception of IAQ, even at the low pollutant concentrations normally found indoors. The relative humidity in these schools ranged between 16% and 75%, with a mean of 38%.

Norback (1995) reported on an investigation of subjective IAQ in14 Swedish schools. He found a relationship between perception of poor IAQ and high room temperature, fleecy wall materials, and VOCs, particularly xylene, limonene, and butanols. Wall-to-wall carpets and fleecy materials had a significant influence on the subjective perception of poor IAQ. These related both to a higher perceived indoor air temperature and higher concentrations of dust and VOCs. Among Norback's study participants, perceptions of air dryness were related to atopy, work stress, poor climate, high room temperature, low air humidity, and high VOC concentrations (indoor/outdoor ratios ranged between 1.5 and 32). A perception of dusty air was related to work stress, teaching responsibilities, and exposure to 2-ethyl-1-hexanol [a microbial VOC (MVOC)].

Walinder et al. (1997) studied the potential for exposure to increased levels of indoor air pollutants in schools to increase swelling of the nasal mucosa. The degree of mucosal swelling was estimated indirectly via the decongestive effect of xylometazolin, measured with acoustic rhinometry. The study was conducted in 39 Swedish schools and included both children and adult staff. Walinder et al. found that the indoor concentrations of VOCs, respirable dust, bacteria, molds, and MVOCs were highest (2–8 times higher) in the school that had the lowest ventilation rate and was naturally ventilated. They concluded that inadequate outdoor air supply in schools may lead to increased levels of indoor air pollutants, resulting in subclinical swelling of the nasal mucosa.

The relationship of asthma to the indoor environment and the occurrence of asthma among school employees was studied by Smedje et al. (1996). Data were gathered among Swedish school employees (1410 subjects) via questionnaire. Data on exposure were collected by monitoring temperature, relative humidity, rate of air exchange, $CO_2$, $NO_2$, formaldehyde, VOCs, MVOCs, respirable dust, molds, bacteria, allergens, and endotoxins in dust. The MVOCs identified were 3-methylfuran, 3-methyl-1-butanol, 2-methyl-2-butanol, 2-pentanol, 2-heptanone, 3-octanone, 3-octanol, 1-octen-3-ol, 2-octen-1-ol, 2-methylisoborneol, geosmin, and 2-isopropyl-3-methoxypyrazine. No significant correlation was found between asthma and air exchange rate, type of ventilation system, visible dampness, amount of fabrics or open shelves in the classroom, room temperature, relative humidity, $CO_2$, respirable dust, viable or total bacteria, viable molds, total MVOCs, formaldehyde, total VOCs, $NO_2$, cat or dog allergens, or endotoxins. Significance was more common among atopic individuals, those who had recently painted in their homes, and those who felt work was stressful.

Asthma was found to be more common among subjects working in schools with higher concentrations of total molds and four MVOCs: 3-methylfuran, 2-heptanone, 1-octen-3-ol, or 2-methylisoborneol. The concentrations found of these MVOCs were very low. Smedje et al. concluded that the relationship to asthma may be principally that the occurrence of MVOCs in indoor air is an indicator of active microorganism growth compared with measurements of airborne microorganisms. MVOCs also have the advantage of providing data about microbial growth inside sealed surfaces. The authors emphasized that these results stress the importance of building, controlling, maintaining, and cleaning schools so that exposure to microbial growth is limited.

*Asthma was found to be more common among subjects working in schools with higher concentrations of total molds and four MVOCs.*

Lundin (1999a) investigated how allergic and nonallergic students perceive their indoor school environment by administering a questionnaire to the students in five high schools in Sweden asking questions about allergies (asthma, hay fever, and eczema), subjective symptoms, annoyance reactions, and the perception of the environment (IAQ, noise, and cleanliness). Fifty-five percent of the students reported having some form of allergy. The findings indicated that allergic students experience discomfort earlier and are more critical about the environment, particularly about the specific factors that affect their health. Allergic students often were bothered by dust and dirt, stuffy or stale air, and passive smoke exposure. All of the students in schools perceived to have a "bad environment" were dissatisfied with the air quality, while all students in a perceived "good environment" were more satisfied with the air quality and cleanliness of the schools. In general the allergic students, as a group, were more critical of these factors.

School surveys outlined by Andersson (1998) revealed that high school teachers and students tend to report different symptom patterns in the same environment. The students reported a higher prevalence of general symptoms, particularly concentration difficulties, than the teachers, irrespective of the IAQ. Students rarely reported a high prevalence of mucous membrane irritation, even in environments with severe dust and moisture problems. Landrus and Axcel (1990) found similar results. Usually, parents of younger children (those in elementary schools and day care) tended to blame the school's IAQ for their children's symptoms. These reporting discrepancies may confound data correlating IAQ and perceived health symptoms.

*Studies of students' and teachers' perceptions of air quality in "bad" environments were inconclusive, but allergic students were more aware of and critical of factors contributing to poor IAQ, and teachers who had worked in a repaired water-damaged school were more sensitive to histamine than those who had not, even after four years.*

Teachers who had worked in a repaired water-damaged school demonstrated increased sensitivity to histamine when compared to teachers in a control school (Rudblad et al. 1999). These teachers had worked in the water-damaged school for more than five years before remediation was done. Prior to remediation in 1995, the teachers were tested for nasal histamine sensitivity by rhinostereometry; the follow-up study indicated that the sensitivity, although diminished, has continued even four years after remediation. The researchers concluded that remaining in an indoor environment with moisture problems for long periods of time is associated with an increased risk for developing nasal hypersensitivity. ❖

## 4 ❖ FACTORS DETERMINING GROWTH OF MICROORGANISMS

In buildings, the conditions for microbial growth vary from structures where water is scarce or seldom available to those where water is constantly present. Systems containing water, such as standing water in cooling coil drain pans or condensed water on cold surfaces (i.e., slab floors, inner walls, or ductwork), favor the growth of bacteria, algae, protozoa, and certain fungi. Consistently high numbers of bacteria in office buildings (excluding food service areas) have been associated mostly with standing water. Most fungi, however, prefer the surfaces of moist materials instead of liquid water (Nevalainen 1993). Buildings that have suffered water damage from leakage or flooding often experience fungal "blooms" that may degrade air quality (Morey 1992). The inside surfaces of outside walls or any surfaces that are temperature clines (wide and/or rapid fluctuations) and foci of condensation may support microbial growth (Flannigan 1992).

In the past few years, fungi have been increasingly linked to SBS (Miller 1992; Samson et al. 1994). The sources and sites of amplification of fungi in indoor environments are highly variable; as a result, establishing a direct link between the presence of fungi and SBS is often problematic. In individual residences, in older buildings with water damage and decay, and in situations following chronic or catastrophic water damage, the harmful effects of fungi are more obvious (Batterman and Burge 1996; Samson et al. 1994, p. 695).

*Fungi have been increasingly linked to SBS in recent years. A number of construction materials support their growth, particularly if those materials are wet and dirty.*

Typical construction materials that can support the growth of fungi include wood, cellulose, hemicellulose, and wallpaper; some organic insulation materials; glues, paints, and mortars that contain carbohydrates or proteins; and textiles, especially natural fibers. Materials that are not easily degraded by fungi—such as mineral wool, metal, polyvinyl chloride and other synthetic polymers, and bricks, tiles, and other such mineral products—still may be extensively colonized by fungi (Ahearn et al. 1995, 1996). In such cases, the fungi do not use the metal or concrete for their growth but, rather, use the water and organic debris on the surface,

including organics absorbed from the air (Nevalainen 1993; Ahearn et al. 1996). Fungi that have been isolated commonly from indoor environments include species of *Aspergillus, Penicillium, Cladosporium, Alternaria* and *Aureobasidium* species (Bisett 1987; Nelson et al. 1988; Ahearn et al. 1991; Mishra et al. 1992; Ahearn et al. 1992a; and Nevalainen 1993). These fungi usually are recovered from sources such as wood rot in domestic interiors, wall coverings, house dust, pets, and houseplants (Mishra et al. 1992; Ahearn et al. 1992b).

**Growth of Fungi in HVAC Systems**

HVAC systems have been associated with increased airborne densities of fungi of various genera, particularly *Cladosporium* and *Penicillium* (Hirsch, Hirsch, and Kalbfleisch 1978; Mishra et al. 1992). Ahearn et al. (1991) reported the colonization of painted metal surfaces of HVAC systems by *Cladosporium* sp. in a study in which airborne conidia appeared in low densities. The fungi were present not in the form of dormant conidia originating from outside air, but as reproducing fungal colonies tightly adhered to the metal surfaces. In Belgium, studies of air-conditioned buildings suggested that the HVAC system was the source of *Penicillium* sp. in the indoor air (Heinemann, Beguin, and Nolard 1994).

Many species of fungi have been isolated from various types of fiberglass used in HVAC systems, particularly when the fiberglass was laden with soil and moisture (Morey 1992; Morey 1993; Bjurman 1993). Ahearn et al. (1992a, 1996) reported the colonization of relatively new fiberglass duct insulation in well-maintained HVAC systems. The facings of the duct insulation were densely colonized with a few species of xerophilic fungi (*Talaromyces* sp. and *Eurotium herbariorum*) or *Penicillium* sp. and *Cladosporium* sp. Colonization appeared related to the use of adsorbed organics and the availability of moisture. Price et al. (1994) and Ezeonu et al. (1994), in laboratory challenge studies, demonstrated that certain types of new fiberglass insulation were readily colonized by certain species of fungi (e.g., *Aspergillus versicolor*) with resistance to formaldehyde residues as a probable selection factor.

Armstrong Laboratory (1992) reports that its studies showed complaints of musty odors and allergic or asthmatic reactions were confined to microbiologically contaminated buildings. The causes of bioaerosol contamination were (1) poorly maintained HVAC systems; (2) high space relative humidities; (3) water-soaked materials, such as ceiling tiles, walls, and carpets; and (4) sick occupants transmitting viruses in the highly recirculated air systems. The most common health complaint from bioaerosol contamination was allergic reactions leading to hypersensitivity pheumonitis, allergic rhinitis, and allergic asthma. Most often,

these symptoms were caused by mold spores or bacteria that had accumulated in the ventilation systems. For microbiological contamination to occur, three conditions must be met: (1) the organism must be able to enter the ventilation system, (2) there must be an amplification site promoting growth to problem levels, and (3) dissemination must occur. The Armstrong report states that the normal indoor mold levels average 60 cfu/$m^3$, and normal bacteria levels average 80–100 cfu/$m^3$. It recommends that indoor mold concentrations in excess of 200 cfu/$m^3$ be considered to signify unacceptable contamination.

**Toxin Production by Fungi**

Mycotoxins are secondary metabolites that are produced by strains of some species of fungi under restrictive environmental conditions, usually during the stationary growth phase. Although the vast majority of mycotoxin studies have involved foods, some intoxications [e.g., "atypical farmers lung," studied by Emanuel, Wenzel, and Lawton (1975)] appear to involve inhalation of mycotoxin-containing dust and/or spores (Jarvis 1990).

Some fungi commonly found indoors—for example *Aspergillus versicolor*, *A. parasiticus*, *A. flavus*, *Penicillium* spp., *Fusarium* spp., *Trichoderma* spp. and *Stachybotrys (atra) chartarum*—may produce a variety of toxins that might become airborne (Smith and Hacking 1983; Bisett 1987; Sorenson et al. 1987; Jarvis 1990; Borgesson, Stollman, and Schnurer 1992; Mattheis 1992; Johanning, Morey, and Goldberg 1993). *Stachybotrys chartarum* is the etiologic agent of stachybotryotoxicosis and has been found to produce a potent cytotoxin, satratoxin H (Bisett 1987; Johanning, Morey, and Goldberg 1993). This toxin is a member of the tricothecene mycotoxin group and is the most active of these mycotoxins (Johanning, Morey, and Goldberg 1993). Trichothecenes produced by *Stachybotrys chartarum* and *Trichoderma* spp. are potent inhibitors of protein synthesis. Toxic effects include dermatitis, respiratory irritation and distress, cardiovascular effects including lowered blood pressure, and immunosuppressive effects (Bisett 1987; Johanning, Morey, and Goldberg 1993). The intestinal tract is also an important target organ, and acute poisoning may lead to severe nausea and diarrhea (Johanning, Morey, and Goldberg 1993). Some of these symptoms were reported for inhabitants of a building found to be significantly contaminated by *Stachybotrys chartarum* (Croft, Jarvis, and Yatawara 1986). Sorenson et al. (1987) later confirmed the presence of trichothecene toxins within the conidia of *Stachybotrys chartarum*.

A review of two buildings reported by Morey (1992) showed that several occupants in one building had developed asthma or allergic respiratory illness that

appeared to be building-related. Air and surface sampling in the building revealed high concentrations of *Aspergillus versicolor* (>20,000 colony-forming units/$m^3$) in the air, as well as *A. versicolor* and *Stachybotrys chartarum* on some contaminated walls. Because conidia of these species potentially contain sterigmatocystin, prolonged exposure to and inhalation of high numbers may present a health hazard (Bisett 1987; Jarvis 1990; Morey 1992; Johanning, Morey, and Goldberg 1993). Our experiences with buildings colonized by both these species have shown them to have an anecdotal association with abnormally high incidences of malaise and absenteeism among occupants. Where toxigenic fungi such as *Aspergillus flavus* or *Stachybotrys (atra) chartarum* are concerned, toxicoses as well as allergenic responses require consideration. The conditions for toxin production appear to be restricted in most cases, and the presence of a potentially toxigenic fungus does not necessarily indicate the presence of the toxin as well.

**Production of Volatile Emissions by Fungi**

A number of fungi are known to produce volatile metabolites on natural substrates. Borgesson, Stollman, and Schnurer (1992) studied the growth of six fungi— *Aspergillus candidus, A. flavus, A. versicolor, Penicillium brevicompactum, P. glabrum,* and *P. roqueforti*—on oat and wheat meals. They found that all species produced a variety of volatile metabolites and that all species produced 3-methylfuran regardless of substrate. Aliphatic alcohols, ketones, and terpenes appear to be the predominant volatiles produced by fungi; as many as 50 volatile compounds have been identified from *Aspergillus clavatus* alone (Bisett 1987; Borgesson, Stollman, and Schnurer 1990; Bjurman and Kristensson 1992a; Bayer and Crow 1993). Some of the more commonly identified VOCs of fungi include geosmin, 3-octanone, 2-octen-1-ol, 3-methyl-1-butanol and 3-methylfuran (Bisett 1987; Borgesson, Stollman, and Schnurer 1992; Mattheis 1992; Bjurman and Kristensson 1992b; Zeringue, Bhatnagar, and Cleveland 1993). The types of volatiles produced are greatly influenced by the type of medium or substrate on which the fungus is growing (Bjurman and Kristensson 1992; Bjurman 1993; Nikulin et al. 1993).

Fungi and actinomycetes have been shown to produce a range of VOCs, including many compounds such as acetone, ethanol, and isopropanol, more commonly associated with solvents and cleaning materials (Bayer and Crow 1993). Bayer and Crow demonstrated that a range of fungi isolated from indoor environments are capable of producing and emitting these compounds into the atmosphere when grown on complex media. At least 26 different

*Fungi and actinomycetes produce a range of VOCs, including many compounds commonly associated with solvents and cleaning materials.*

volatile compounds were found to be produced by the fungi in this study, including known carcinogens such as benzene.

Strom et al. (1994) investigated the production of MVOCs as a means to detect the occurrence of fungi and bacteria within building constructions. A significant increase in the concentration of MVOCs was observed in houses with microbial odor problems, compared with unaffected houses and outdoor air samples. Microbial analysis of damaged building materials from houses with odor problems showed highly significant differences from the corresponding material collected from unaffected houses. Additionally, it was found that MVOCs diffuse through plastic sheeting used as water vapor barriers. Therefore, these barriers do not prevent the diffusion of the MVOCs and permit contamination of the indoor air with microbial odors.

Strom et al. identified the representative MVOC compounds that indicate microbial activity to be 3-methylfuran, 2-methyl-1-propanol, 1-butanol, 3-methyl-1-butanol, 3-methyl-2-butanol, 2-pentanol, 2-hexanone, 2-heptanone, 3-octanone, 3-octanol, 1-octen-3-ol, 2-octen-1-ol, 2-methylisoborneol, geosmin, and 2-isopropyl-3-methoxypyrazine. The primary odor-causing compounds are probably geosmin, 2-methylisoborneol, and 2-isopropyl-3-methoxypyrazine. These three compounds have an "earthy" odor. A mushroom-like odor is produced by 1-octen-3-ol and 2-octen-1-ol. These are thought to be the source of the "musty" odor.

Ezeonu et al. (1994) demonstrated the production of 2-ethyl hexanol, cyclohexane, and benzene by a mixed fungal population colonizing fiberglass insulation. *Aspergillus versicolor* and *Chaetomium globosum* have both been shown to produce geosmin, a VOC with a distinct "earthy" odor (Bjurman and Kristensson 1992a,b). Geosmin has also been associated with *Streptomyces* sp. isolated along with a number of fungal species from an odor-producing HVAC system (Crow 1993). Moisture requirements for volatile production by fungi also may be different from those for growth (Moss 1991; Bjurman and Kristensson 1992a; Nikulin et al. 1993). The possibility exists that VOCs produced by fungi at one location in a structure could influence the growth of other fungi at remote sites through dissemination of these compounds by mechanical ventilation systems. This influence could indirectly contribute to further degradation of air quality as a result of increased airborne loading of conidia, sclerotia, or hyphal fragments.

Horner, Morey, and Worthan (1997) performed sampling in an extensively water-damaged school. The students and teachers were complaining of musty odors and allergic responses. *Cladosporium cladosporidoides* dominated all of the outdoor air samples and was collected in 99% of the indoor air samples. The total concentrations of the culturable molds were lower indoors than outdoors when the

ventilation system was operating, indicating that airborne exposure to the fungi indoors was similar to the outdoor exposure. However, dust sampling of the carpet, air supply louvers, and duct liner surfaces indicated microbial amplification. MVOCs were also measured, and 2-octen-1-ol was detectable at most of the sampling locations. MVOCs were not detectable in the noncomplaint or outside samples.

Joki et al. (1993) found that the respiratory symptoms of people living in moldy houses may be caused by MVOCs. These researchers studied the effects of MVOCs from *Penicillium*, *Trichoderma viridae* and two actinomycete strains, along with those from *Klebsiella pneumoniae* lipopolysaccharide on tracheal tissue in vitro. *Trichoderma viridae, Penicillium*, and the actinomycete strains showed a tendency towards ciliostimulation. The effect was similar to the ciliostimulatory effect brought about by respiratory infections. Joki et al. concluded that the MVOCs could adversely affect the mucociliary defense in respiratory airways. ❖

## 5 ❖ HUMIDITY CONTROL AND THE IMPACT ON IAQ

### Impact of High Space Humidity

As discussed previously, moisture is a key factor in the growth and amplification of mold, fungi and other microbes. As a result, problems with these organisms can be severe in air-conditioned buildings located in humid environments, especially the southern United States and tropical climes. The accumulation of moisture on or in the envelope of buildings in these climates is strongly influenced by indoor temperature and outdoor humidity. Mold growth typically occurs on internal surfaces of the external walls or floors, since these surfaces are cooled by the air-conditioning system to below or near the dew point temperature of humid air infiltrating into the building envelope (Flannigan and Morey 1996). Moisture enters the building because of (1) leakage of rain into the wall cavities, (2) movement of humid air into the interior because of poor building construction, (3) water vapor diffusion from the humid exterior to the dry interior, and, perhaps most common, (4) entry through the conventional HVAC system when the supply air fan is operated while the cooling coil is cycled off.

Overcooling of indoor spaces results in moisture and mold problems in buildings in climates where the outdoor dew point temperature is at or above about 25°C (77°F). The problems can become severe when the internal surface temperatures drop a few degrees below 25°C and the likelihood increases that the surface relative humidity will exceed 65% (Flannigan and Morey 1996). Ironically, when building occupants feel clammy because of high space humidity, the typical response is to lower the space thermostat setting. The result is that the space cools further, most often increasing the space relative humidity along with the likelihood of condensation of moisture on supply air ducts, floors, and other building surfaces.

*Moisture is a key factor in the germination of mold, fungi, and other microbes; and therefore, problems with these organisms can be severe in air-conditioned buildings in humid climates because of overcooling of indoor spaces.*

Moisture problems can also be a function of the occupancy load (Merrill and TenWolde 1989). High occupant densities, such as those in schools, generally result in a relatively high degree of moisture release into room air. When there is a combination of high occupant densities (such as in schools), poor ventilation, and cold external walls, often moisture, dirt accumulation, and mold growth occurs in walls and on building surfaces. These can be controlled by proper ventilation with preconditioned (dehumidified air at room neutral temperature) outdoor air (Lstiburek 1994).

*In eight schools studied by Fischer, improved humidity control, reduced coil condensate, and the low relative humidity maintained by a DWERS helped avoid microbial problems and illness.*

Fischer (1996) concluded that improved humidity control, reduced coil condensate, and the low (60%) relative humidity maintained in the supply air ductwork by a DWERS helps to avoid microbial problems and illness in humid climates. Fischer based his conclusions on a survey of eight schools investigated. The schools were specifically chosen because each had experienced serious IAQ problems, had subsequently been retrofitted with desiccant-based total energy recovery systems, and had since operated with these systems for at least 2 years. His survey revealed that in each of the schools, the modifications resulted in a complete and lasting resolution of the IAQ problems.

Davanagere et al. (1997) evaluated the impact of ASHRAE Standard 62-1989 on the sensible and latent cooling loads in Florida's hot and humid climate. ASHRAE Standard 62-1989 (ASHRAE 1989) raised the minimum outdoor air requirements for ventilating school classrooms by a factor of 3 over the previous ASHRAE Standard 62-1981. Davanagere and associates performed an annual building energy simulation for a protypical school in three Florida cities—Miami, Orlando, and Jacksonville—analyzing the performance of a conventional HVAC system and several alternate technologies. The simulation results indicated that the conventional HVAC system will have problems maintaining relative humidity levels at or below 60% in Florida schools at the specified ASHRAE ventilation rate of 7.5 L/s (15 cfm/person). The chiller size, energy usage, electrical peak demand, and operating costs were predicted to significantly increase. The hours above 60% relative humidity are outlined in Table 1.

The alternate technologies considered in the Davanagere et al. study are shown in Table 2; those that were predicted to maintain indoor humidity levels below 60% relative humidity for most of the occupied hours are indicated by a check mark. Gas-fired desiccant systems will use the least amount of electrical energy of the pretreatment alternate technologies, but natural gas is required to regenerate the

**Table 1. Impacts of ASHRAE Standard 62-1989 on classroom humidity levels in three Florida cities (Davanagere et al. 1997)**

| Description[a] | Miami | Orlando | Jacksonville |
|---|---|---|---|
| *Total hours[b] above 60% RH at* | | | |
| Std. 62-1981 ventilation rate | 3675 | 3703 | 4042 |
| Std. 62-1989 ventilation rate | 5253 | 4196 | 4451 |
| *Occupied hours[c] above 60% RH at* | | | |
| Std. 62-1981 ventilation rate | 204 | 189 | 196 |
| Std. 62-1989 ventilation rate | 584 | 359 | 332 |

[a] RH = relative humidity
Standard 62-1981 ventilation rate = 5 cfm (2.5 L/s) per person
Standard 62-1989 ventilation rate = 15 cfm (7.5 L/s) per person.
[b] Total hours = occupied + unoccupied hours.
[c] Total number of occupied hours = 1512 per year.

desiccant wheel. Operating costs should be reduced when thermal energy storage systems are used. Davanagere et al. concluded that a conventional HVAC system will not be able to maintain the proper indoor humidity levels and that pretreatment of the outdoor air with these alternate technologies will provide better humidity control in the occupied areas.

Baughman and Arens (1996) summarize numerous health-related effects associated with high and low indoor relative humidity, including mycotoxins and VOCs produced by fungi. Bayer, Crow, and Noble (1995) investigated schools with complaints of rashes and respiratory illnesses. The investigation focused on microbial growth, which was identified in all cases. It concluded that many of the airborne VOCs appeared to be microbial in origin. Bayer and Downing (1992) reported on three schools using packaged HVAC equipment that were investigated and found to have serious humidity problems, even with only small percentages of intermittent outdoor air supplied to the occupied space.

The Armstrong Laboratory (1992) study cited microbial contamination in nearly 50% of the buildings investigated. Its authors stated that, based on their findings, carpet, curtains, furniture, and so on can absorb enough moisture at space humidities greater than 65% to promote microbial growth. At relative humidities greater than 70%, according to the report, VOCs are emitted at greater rates than at below 60%. The Armstrong report recommends that buildings be operated to maintain the space relative humidity between 40 and 60%. This study agrees well

with ASHRAE Standard 62-1989, which recommends that space relative humidity be maintained at between 30 and 60%.

**Table 2. Alternative technologies to meet ASHAE Standard 62-1989 in Florida schools (Davanagere et al. 1997)**

| | |
|---|---|
| *Demand-control ventilation* | |
| *Technologies to pretreat outdoor air* | |
| Enthalpy recovery wheels | ✔ |
| Gas-fired desiccant systems | ✔ |
| 100% outdoor air DX units | ✔ |
| Heat-pipe-assisted cooling coils | ✔ |
| Chilled-water coils | ✔ |
| Chilled-water coils combined with partial thermal energy storage | |
| Chilled-water coils combined with full thermal energy storage | |
| *Baseline systems* | |
| Thermal partial energy storage system | |
| Thermal full energy storage system | |
| *Cold air distribution systems* | ✔ |
| Partial thermal energy storage | |
| Full thermal energy storage | |
| Liquid refrigerant overfeed system. | |

## Impact of Low Space Humidity

Although too much airborne moisture (humidity above 70% relative humidity) can exacerbate the symptoms of people with asthma and allergies, air that is too dry (below 30% relative humidity) can cause eye, nose, and throat irritation; discomfort for contact lens wearers; nosebleeds; and static electric shocks (Quinlan et al. 1989). The Armstrong Laboratory (1992) report states that relative humidities of less than 40% cause physiological effects leading to environmental discomfort and dissatisfaction. The symptoms include dry and sore nose and throat, bleeding nose, sinus and tracheal irritation, dry scratchy eyes, inability to wear contact lenses, and dry, itchy, flaky skin. Low relative humidities contribute to an increase in respiratory illness by weakening the defense provided by the mucous membranes. This report recommends that relative humidity be controlled between 40 and 60%, and that humidity control devices be installed in the HVAC systems because "natural" humidification does not maintain the relative humidity of a building at 40–60% throughout the entire year.

A study conducted by Arundel et al. (1986) concluded that influenza virus cultivated in human cells survived at the highest rate when exposed to low relative humidities (20%), survived at a minimum rate at between 40% and 60% RH, and increased again after exposure to high humidity (70–80%). A plot of the morbidity

from colds and low indoor humidity has been shown by Hope-Simpson (1958) to have a "high correlation."

Three different researchers studied the relationship between humidification and absenteeism (Sale 1972; Ritzel 1996; Green 1974, 1985). Sale and Ritzel studied controlled populations of kindergartens to determine the relationship between respiratory illness and space relative humidity. Both studies found that in schools where the humidity was increased with humidifiers, the absenteeism was 40–50% lower than in unhumidified schools. They reported a decrease in colds, sneezing, sore throats, and fever experienced by the children in spaces humidified in winter. Sale included approximately 500 kindergarten children in the study, investigating the impact of humidification in the home in conjunction with humidification in the school. The students were divided into four groups (the rate of absenteeism is in parentheses): humidification at home and at school (1.3%), humidification at school only (3.9%), humidification at home only (5.1%), and no humidification (7.1%).

Green (1974) compared the absenteeism in 18 schools, with a total of approximately 4800 students, for 11 years. Some of the schools were humidified to greater than 25% and others were not humidified. There was a statistically lower rate of absenteeism in the humidified schools. He concluded that a possible reason for the reduction in absenteeism may have been a reduction in disease transmission.

Fischer (1996) concluded that the free humidification provided by total energy recovery systems can maintain the space relative humidity above 30% during all but the most extreme winter time conditions, and can thereby reduce the incidence of respiratory illness and absenteeism in classrooms located in colder climates. ❖

## 6 ❖ VOCs AND OTHER CHEMICAL COMPOUNDS THAT AFFECT IAQ

Downing and Bayer (1993) investigated the relationship between ventilation rate and IAQ in classrooms. Their investigation was conducted in a 2-year-old school in Georgia that had experienced serious IAQ problems and SBS. Samples were collected and analyzed for VOCs, formaldehyde, $CO_2$, temperature, and humidity. Downing confirmed in this study that 15 cfm of outdoor air per student, provided continuously, was required to maintain $CO_2$ concentrations at levels below 1000 ppm. The recommendation is made that classrooms, both new and existing, be provided with at least 15 cfm per student of outdoor air on a continuous basis during school hours. It was found that VOC concentrations exceeded 1000 $\mu g/m^3$ when only 5 cfm per student was provided, even on a continuous basis, and that the occupants were dissatisfied with the air quality at these conditions. Tucker (1986) indicated that this level of VOCs is an indication of potential IAQ problems. Hydrocarbon levels measured in the classroom were found to be nine times higher than those measured outdoors when the outdoor air quantities were cycled with the cooling coil. Indoor hydrocarbon levels were reduced to approximately the outdoor concentration levels when 15 cfm of outdoor air per student was provided on a continuous basis and humidity was controlled.

*In a Georgia school, when the HVAC system was modified to include a DWERS that provided a continuous outdoor air supply of 15 cfm per student and controlled the space relative humidity at between 50 and 55%, all complaints related to IAQ — respiratory and allergy problems, headaches, and lethargy — ceased.*

The school investigated by this study used 3-ton rooftop-packaged systems operating at a maximum of 5 cfm per student. The relative humidity exceeded 70% for extended time periods (see Fig. 1), resulting in microbial amplification. With the original HVAC system in operation, there was visible mold growth on building surfaces, ceiling tiles, and books. The IAQ complaints and illnesses included respiratory and allergy problems, headaches, and lethargy. When the HVAC system was modified to include a DWERS that provided a continuous outdoor air supply of 15 cfm per student and controlled the space relative humidity at between 50 and 55%, all complaints

regarding IAQ stopped. They have not returned after approximately 5 years of operation.

As discussed previously, Bayer and Crow (1993); Bjurman and Kristensson (1992b); Borgesson, Stollman, and Schnurer (1992); Nikulin et al. (1993); Strom et al. (1994); and others documented the emission of a wide range of VOCs and mycotoxins associated with microbial activity in buildings. These emissions have been documented in both dry climates (i.e., Sweden) and humid climates. As shown in the Downing and Bayer (1993) investigation, the measurement of specific VOCs can serve as an effective marker for identifying microbial activity. According to this investigation, continuous ventilation may have served to purge the high levels of VOCs resulting from microbial activity, as well as limit the possibility that VOCs produced by fungi at one location would enhance the growth of other fungi at other sites throughout the facility.

ASHRAE Standard 62-1989 (ASHRAE 1989) recommends that indoor $CO_2$ levels not exceed 1000 ppm for satisfactory occupant comfort. Experimental studies have demonstrated that outdoor air ventilation of approximately 7.5 L/s will control human body odor so that about 80% of unadapted people will find the odor level acceptable. That same level of body odor acceptability occurs at a $CO_2$ concentration approximately 650 ppm above the outdoor concentration (ASTM 1998; Cain et al. 1983). Bakke (1999) states that "the scientific basis for the $CO_2$-criterion of 1000 ppm is on studies of acceptability of air quality for persons entering the room—that is, perceptions in non-adapted persons. There is not sufficient or conclusive evidence for effects on health or productivity when controlled for temperature, humidity and other pollutants." He concludes that although the ventilation criterion has been insufficiently studied, the prevailing ventilation requirements are founded on experience and include a proper margin of safety.

A number of researchers have used $CO_2$ levels to assess IAQ and calculate ventilation rates, but incorrect assumptions and misinterpretation of data can lead to erroneous conclusions about the adequacy of ventilation air and health impacts (ASTM 1998; Bearg, Turner, and Brennan 1993; Persily 1997; Mudarri 1997; Persily and Dols 1990). Indoor $CO_2$ concentrations generally are dependent on occupancy (which may change significantly during the day); changes in occupant activity levels; and the performance, limitations, and characteristics of the ventilation system. In addition, measurement of $CO_2$ levels are affected by the limitations and accuracy of sampling methods and instrumentation, and sampling locations, frequency, and times.

Inadequate and inefficient ventilation of occupied zones has been associated with higher $CO_2$ levels and increased frequency of IAQ complaints by many researchers (Casey et al. 1995; Godish et al. 1986; Rajhans 1983; Salisbury 1986; Skov et al. 1987; Turiel et al. 1983; Wallingford and Carpenter 1986). Most researchers cite the use of the ASHRAE guideline limit of 1000 ppm for $CO_2$ (ASHRAE 1989) as a surrogate for a lack of fresh air supply in occupied spaces. The Ontario Ministry of Labor (Rajhans 1989) linked $CO_2$ levels and the frequency of occupant complaints (Table 3) and also set a guideline of 1000 ppm $CO_2$ as an indicator of insufficient fresh air supply.

*Inadequate and inefficient ventilation of occupied zones has been associated with higher $CO_2$ levels and increased frequency of IAQ complaints by many researchers.*

The Maryland Public Schools Indoor Air Quality guideline (Maryland State Department of Education 1987) lists acceptable outdoor air ventilation rates for different types of spaces in schools to achieve an acceptable level of IAQ by controlling $CO_2$ levels to 1000 ppm or less (Table 4).

A study by Quinlan et al. (1989) notes that when the indoor $CO_2$ level reaches 1000 ppm, "it is likely that some of the occupants will begin to complain." These complaints "are not directly related to $CO_2$, but to an inadequate supply of fresh air and the resulting increase of various contaminants inside the building. At higher levels of $CO_2$ a greater number of people will feel uncomfortable." This study advises that the $CO_2$ level be maintained at a level below 800 ppm.

**Table 3. Ontario Ministry of Labor findings on relationships between extent of complaints regarding IAQ and $CO_2$ levels and ventilation rates (Rajhans 1989)**

| Extent of complaint | $CO_2$ level (ppm) | Ventilation rate/person | |
|---|---|---|---|
| | | cfm | L/s |
| Occasional complaints, esp. with rise in air temperature | 600 | 35 | 16.5 |
| More prevalent complaints | 800 | 21 | 10 |
| Insufficient makeup air; more general complaints | 1000 | 15 | 7 |

**Table 4. Maryland's requirements for outdoor air ventilation rates in schools (Maryland State Department of Education 1987)**

| Type of space | Est. max. occupancy (people/1000 ft$^2$) | Ventilation rate | | Notes |
|---|---|---|---|---|
| | | cfm/person | cfm/ft$^2$ | |
| Classroom | 50 | 15 | — | |
| Laboratory | 30 | 20 | — | a |
| Training shop | 30 | 20 | — | a |
| Music room | 50 | 15 | — | |
| Library | 20 | 15 | — | |
| Corridor | — | — | 0.1 | |
| Auditorium | 150 | 15 | — | |
| Smoking lounge | 70 | 60 | — | |
| Office | 7 | 20 | — | |
| Conference room | 50 | 20 | — | b |
| Reception area | 60 | 15 | — | |
| Locker room | — | — | 0.5 | |
| Gymnasium (playing floor) | 30 | 20 | — | |
| Swimming pool | 30 | 20 | — | c |
| Spectator area | 150 | 15 | — | |
| Public restroom | — | 50 | — | d |
| Darkroom | — | — | 0.5 | |
| Kitchen | 20 | 15 | | e |
| Cafeteria | 100 | 15 | | |

*Notes:*
[a] Special contaminant control systems may be required for processes or functions.
[b] Supplementary tobacco smoke removal equipment may be required.
[c] Higher values may be required for humidity control.
[d] Value given is cfm per water closet or urinal.
[e] Makeup air for hood exhaust may require more ventilation air. The sum of outdoor air and transfer air of acceptable quality from adjacent spaces should provide an exhaust rate of not less than 1.5 cfm/ft$^2$.

The Armstrong Laboratory (1992) report concludes that $CO_2$ concentration is a useful indicator of inadequate makeup air and that concentrations above 600 ppm are the cause of some specific IAQ irritations, for which these researchers have excellent

*A group of researchers from Armstrong Laboratory found that $CO_2$ concentrations in excess of 600 ppm cause significant physiological effects, such as fatigue, drowsiness, lack of concentration, and sensations of breathing difficulty.*

correlations. They found that 15–33% of the population will have symptoms from $CO_2$ exposure at 600–800 ppm, approximately 33–50% will have symptoms at 800–1000 ppm, and virtually 100% will show symptoms at greater than or equal to 1500 ppm. Armstrong Laboratory's observations indicate that $CO_2$ concentrations exceeding 600 ppm may result in physiological complaints: fatigue, drowsiness, difficulty concentrating, and difficulty breathing. The Armstrong researchers developed a satisfaction model based on data from medical interviews and questionnaires in 18 buildings. Based on this model and an 80% satisfaction rate, they calculated that the $CO_2$ levels should not exceed 600 ppm, and that when the $CO_2$ concentration was 1000 ppm a 42% satisfaction rate was predicted. Based on this model, the report recommends that $CO_2$ concentrations not exceed 600 ppm, a level that can be achieved with a minimum of 40 cfm per person.

Bakke and Levy (1990) investigated the IAQ in six kindergartens during the winter in Norway. They found a correlation between the highest $CO_2$ levels and highest relative humidity and the most frequent complaints of "dry air" and eye irritation (which is usually associated with dry air). The complaints of dry air were most frequent at the kindergartens with the lowest ventilation rate and the highest relative humidity. Bakke and Levy conclude that high $CO_2$ levels and high relative humidity may indicate that a building has a ventilation rate that is too low.

Seppanen, Fisk, and Mendell (1999) reviewed available literature for the association of ventilation rates and $CO_2$ concentrations with health or perception outcomes. were not able to determine a clear threshold value for $CO_2$ levels below which further reductions in concentration were not associated with further decreases in SBS symptoms. However, 7 of 16 studies suggested that the risk of SBS symptoms continued to decrease with decreasing $CO_2$ concentrations below 800 ppm.

Correlations between pupils' health and performance and $CO_2$ concentrations in classrooms were determined by Myhrvold, Olsen, and Lauridsen (1996). These researchers conducted physical measurements of $CO_2$ and other indoor air parameters, distributed questionnaires, and administered a Swedish Performance Evaluation (SPES) test to students in eight schools in Sweden. During the sampling days of this study, they found the following $CO_2$ exposure levels among the students:

| *% of students* | *$CO_2$ level* |
|---|---|
| 48.9% | 0–999 ppm |
| 24.9% | 1000–1499 ppm |
| 26.4% | 1500–4000 ppm |

These researchers divided the reported health symptoms into two categories: (1) headache, dizziness, heavy-headedness, tiredness, concentration difficulties, and unpleasant odor; and (2) throat irritation, nose irritation, runny nose, coughing fits, short-windedness, runny eyes, and irritations of the upper airway. The SPES test

was administered to students between the ages of 11 and 20 to measure performance. Since age proved to be a confounder, only the results from pupils 15 years old or older were used in the statistical data interpretations. Strong correlations were found between $CO_2$ and the first category of health symptoms, particularly when the $CO_2$ levels were 1500 ppm or greater. Weaker correlations were found between $CO_2$ levels and the second category of health symptoms. Myhrvold, Olsen, and Lauridsen also showed a correlation between $CO_2$ concentrations and poor performance but were not able to show statistically significant differences between the three $CO_2$ concentration groups.

Ligman et al. (1999) reported on $PM_{10}$ and $PM_{2.5}$ data collected in U.S. elementary and secondary schools. The overall results are presented in Table 5. In general, the airborne particulate matter levels were higher in schools than in office buildings and were in higher concentrations in the schools than in the ambient outdoor air.

**Table 5. Particulate matter levels in schools (Ligman et al. 1999)**

| Type of building | Location (state) | Sample results | Concentration (geometric mean, $mg/m^3$) |
|---|---|---|---|
| Office | AZ, CA, CO, FL, GA, LA, MA, MD, MI, MN, MO, NE, NV, NY, OR, PA, SC, TN, TX, WA | $PM_{10}$ indoor | 12 |
| | | $PM_{2.5}$ indoor | 8 |
| | | $PM_{10}$ outdoor | 26 |
| | | $PM_{2.5}$ outdoor | 16 |
| School | CA, CO, FL, KS, MN, NJ, NM, NY, TX, WA | $PM_{10}$ indoor | 46 |
| | | $PM_{2.5}$ indoor | 13 |
| | | $PM_{10}$ outdoor | 19 |
| | | $PM_{2.5}$ outdoor | 9 |

Meyer et al. (1999) conducted an epidemiological study that suggested an association between building-related symptoms and dust with a high inflammatory potential. Seventy-five schools in Copenhagen, Denmark, were included in a cross-sectional epidemiological study. The building-related symptoms analyzed were eye irritation, nasal irritation, nasal congestion, throat irritation, flushing or irritated facial skin, headache, fatigue, and lack of concentration. Symptom frequencies were grouped in two categories: (1) "never/seldom" plus "now and then," and (2) "several times a week" plus "daily." The inflammatory potential of dust collected from floors, surfaces, and exhaust ducts was tested in an in vitro bioassay with human lung epithelial cells. For all eight building-related symptoms, the researcher saw a significant increase in symptom prevalence with increasing exposure index. ❖

## 7 ❖ CONTROL OF INDOOR ENVIRONMENTS WITH HVAC SYSTEMS

The quantity of air in a modern building is highly dependent upon the operation of its HVAC system. HVAC systems are designed to mix a given amount of outdoor air with some amount of recirculated air, condition this mixture, and distribute it to the occupied space (Morey 1988). The amount of recirculated air in the mixture varies from system to system and building type to building type. In the U.S. service sector (commercial, institutional, and government buildings), the estimated energy consumed for ventilation is about one-fourth of the total service-sector building energy use (Orme 1998). Climate has a significant impact on the amount of energy consumed to condition ventilation air. In the hot and humid climate of Miami, removal of moisture from ventilation air consumes 86% of the energy usage in buildings (Seppanen, Fisk, and Mendell 1999). Therefore, energy-efficient technologies that provide optimum indoor air environments are critically needed.

Large buildings typically use chilled water systems with large central air handling systems that, if sized correctly, are capable of conditioning the outdoor air quantities recommended by ASHRAE Standard 62-1989. A conventional variable-air-volume (VAV) system distributes approximately 1.5 cfm/ft$^2$ of 56°F air, of which typically 20% is outdoor air and 80% is recirculated air. However, it has been shown that even if 15 cfm per person of outdoor air is provided to the central air handling system, it is possible to have poor air circulation within individual zones. The lack of circulation causes contaminant buildup either continuously or intermittently at low-flow (part-load conditions) within a typical VAV system (Meckler 1992). For this reason, ASHRAE recommends increasing the outdoor air quantity delivered to the VAV system beyond 15–20 cfm per person (the Z factor) to ensure adequate outdoor air to all zones (Brady 1996).

Seppanen, Fisk, and Mendell (1999) reviewed literature and determined that a significant association has been reported between lower ventilation rates (below the normally encountered range of 2.5–30 L/s per person) and increased health effects and worsened air quality perception. Of 31 studies of buildings with ventilation

rates below 10 L/s per person, 27 reported a significant worsening of health or perceived IAQ. Mendell (1993), in a review of six ventilation and air quality studies, reported a consistent association between higher SBS symptom prevalence and outdoor air ventilation rates below 10 L/s per person. In a study in Swedish schools, Walinder et al. (1998) measured nasal patency and biomarkers for allergic reactions associated with ventilation rate (ranging from 1.1 to 9 L/s per person). This study did not find a significant association, which suggested a pollutant source in the schools buildings, such as emissions from building materials or microbial emissions from moisture-damaged structures.

Seppanen, Fisk, and Mendell (1999), using on a calculated relative risk of 1.1 determined by Jaakkola and Miettinen (1995), estimated that a 5 L/s per person increase in ventilation rate in U.S. office buildings would reduce the proportion of occupants with frequent upper respiratory symptoms from 25% to 16%. Similarly, they calculated that a 5 L/s person decrease in ventilation rate would increase the proportion of occupants with frequent upper respiratory symptoms from 25% to 40%. Their predictions suggest that increasing the ventilation rate in schools may have a significant impact on chronic and acute upper respiratory symptoms in children, so long as the humidity is controlled within acceptable levels.

In large buildings, an HVAC system may serve to transport microorganisms from the locus of contamination (e.g., a humidifier or moist insulation) to the vicinity of sensitive occupants (Morey 1988, 1992; West and Henson 1989; Turner et al. 1993, 1996a; Price et al. 1995; Batterman and Burge 1996). For this and other reasons discussed previously, both outdoor air ventilation and humidity control are essential issues in the relationship between HVAC systems and IAQ.

Innovative designs have been employed in large buildings to ensure adequate humidity control and outdoor air delivery with traditional VAV systems. For example, a cold air distribution system can be applied so that all of the air processed by the VAV air handling system is outdoor air (Meckler 1992). Bayer and Downing (1991) investigated a 30-story building that successfully used a total energy recovery preconditioning unit to provide a constant supply of outdoor air to each VAV system on a floor-by-floor basis. This system ensured that approximately 20 cfm of outdoor air per person was delivered even as the return air percentage varied between 80 and 20% at

*The use of innovative HVAC designs in large buildings can ensure adequate humidity control and outdoor air delivery with traditional VAV systems.*

the VAV air handling system. Various contaminants measured— including VOCs, $CO_2$, formaldehyde, and others— confirmed the effectiveness of this design approach.

The vast majority of facilities constructed each year in the United States are considered small buildings (i.e., three stories or less). These facilities—which include small offices, schools, restaurants, municipal buildings, and nursing homes—typically use packaged HVAC equipment because of its low cost, compact size, and ease of installation and maintenance. Unfortunately, packaged equipment is far more limiting with respect to outdoor air delivery and humidity control capability than are the large chilled water systems used in large buildings. Packaged systems have been designed to provide only a modest percentage of outdoor air on an intermittent basis in order to minimize cost. When they are operated with continuous outdoor air or an increased percentage of outdoor air, comfort and humidity control is often lost (Downing and Bayer 1993; Henderson and Rengarajan 1996).

As a result, small facilities often are not designed and/or operated in accordance with ASHRAE 62-1989. Besides the inability of packaged equipment to accommodate increased outdoor air ventilation rates and maintain space comfort, reasons include the perception that there is a significant first-cost premium, potentially high operating costs, and a general ignorance of IAQ on the part of many building owners and installation contractors. Many small buildings are constructed on a design/build basis, with the installing contractor (not a consulting engineering firm) completing the mechanical design with the primary objective of minimizing the HVAC system installation cost.

Until recently, few economical options have been available to design engineers and contractors that combine effectively with conventional packaged HVAC equipment and enable it to perform as required while accommodating the recommendations made by ASHRAE 62-1989 (i.e., increased outdoor air provided on a continuous basis to the occupied space). As a result of these and other factors, many small buildings have been designed with an inadequate supply of outdoor air being provided on an intermittent basis. Two of the most common design schemes are the following:

- Using rooftop packaged equipment that provides approximately 10–15% outdoor air. In very cold or hot/humid climates, the fans in these units are typically cycled

with the heating source (burner) or cooling source (coil), to avoid dumping of cold air during the heating mode and poor humidity control during the cooling mode.

- Using rooftop packaged equipment or split systems with little or no outdoor air being provided to the space by the HVAC equipment. Infiltration through door and building leaks is assumed to deliver "adequate" outdoor air.

As the research summarized in this paper indicates, compromising either the continuous supply of outdoor air or proper humidity control can result in serious IAQ problems, especially in school facilities. During the air-conditioning season, the intermittent use of ventilation causes extreme variation in indoor contaminant concentrations and space relative humidity, which may result in absorption of water into porous materials (West and Henson 1989; Morey and Williams 1991). The availability of both water and nutrients controls microbial growth in porous insulation. Water condensation alone is not a problem as such, but if the temperature is sufficient and organic material is present, viable fungal spores will have an opportunity to germinate and proliferate (Morey and Williams 1991).

Fischer (1996) concluded that desiccant-based recovery systems can be easily and cost-effectively integrated with conventional packaged HVAC equipment to provide the increased outdoor air quantities and humidity control recommended by ASHRAE 62-1989 and shown to be critical by the research summarized in this paper. In his investigation, Fischer summarizes first-cost information provided by the design engineers for seven different school projects which demonstrates that the ASHRAE 62-1989 recommendations can be accommodated with a cost-effective mechanical design. In each project, the benefits of improved IAQ were found to far outweigh any incremental investment by the engineers, owners, and occupants required to incorporate the required desiccant-based preconditioning equipment.

*Desiccant-based energy recovery systems, dehumidification, and cooling systems and various other overcooling with reheat approaches can dehumidify the outdoor air stream provided to the occupied space or to the intake of the conventional HVAC equipment. Thus, downsized packaged equipment linked with a preconditioning system can be cost-effective means of accommodating the ventilation and humidity control needs recommended by ASHRAE.*

Investigations by Bayer and Downing (1991), Coad (1995), and Downing and Bayer (1993) all support the need to improve the performance of packaged HVAC equipment through preconditioning the outdoor air supplied to a building so that

the latent load (humidity) is decoupled from the sensible (temperature) load that is effectively handled by the packaged HVAC equipment. The sensible load can then be easily managed, usually with smaller-capacity packaged equipment, using simple thermostat controls and on a room-by-room basis if desired. Such an arrangement provides improved comfort and energy efficiency and is probably the most cost-effective way of accommodating the ASHRAE 62-1989 guidelines.

Numerous articles and manufacturer case histories are available to demonstrate how technologies such as desiccant-based energy recovery, dehumidification, and cooling systems and various other overcooling with reheat approaches have been applied successfully to dehumidify the outdoor air stream provided directly to the occupied space or to the intake of the conventional HVAC equipment (HPAC 1996a, 1997; Gatley 1993; Turner et al. 1996b). These approaches have shown that downsized packaged equipment linked with a preconditioning system can be cost-effective to install and operate and can accommodate the ventilation and humidity control needs recommended by ASHRAE. In addition, several desiccant system design approaches have been shown to deliver air through the ductwork that is well below saturated conditions, operate with dry cooling coils, remove contaminants from the outdoor air and kill bacteria, all of which are beneficial to improving indoor environments.

An alternative approach was used by one engineering firm in a south Florida high school (HPAC 1996b). The school board requested that the outside air flow rate be lessened to 5 cfm per person so that the operating costs and humidity control needs would be reduced. The problem with this approach, as was recognized by the engineering firm, was that lessening the amount of fresh ventilation air probably would lead to costly maintenance and operations problems, and to occupant health and comfort problems. The engineering firm chose to use increased filtration, rather than innovative ventilation technology, applying the Indoor Air Quality Procedure in ASHRAE Standard 62-1989. Eighty-five percent efficiency particle filters and 80% carbon-absorbing gaseous removal filters were installed. The suppliers of the filters were required to provide written documentation that the filtration devices would provide the equivalent IAQ that would be achievable with increased quantities of outside air, documenting compliance with ASHRAE 62-1989. The report does not present longitudinal air testing data in the school to prove the maintenance of adequate indoor air quality in the school.

Wheeler and Abend (1991) examined the occupancy and operational characteristics of typical Maryland public schools. They then constructed a model to assess

alternate HVAC design strategies and concepts that would minimize the adverse energy consequences of the ventilation requirements in ASHRAE Standard 62-1989. At maximum occupancy, this standard recommends an outdoor air ventilation rate of 0.75 cfm per $ft^3$ of floor space. Wheeler and Abend list the environmental contaminants of interest in a classroom setting to be odorous bioeffluents, microorganisms, and VOCs. The major HVAC system objectives in a classroom are low initial and operating costs; thermal comfort; humidity control; pathogen removal; and odor dilution. These authors propose using a conventional variable air volume (VAV) system with fan-powered, series arrangement terminals. The air supply to the room would be constant, and recirculated air would be filtered. Wheeler and Abend also consider displacement ventilation from floor to ceiling to be a promising alternative approach. When the model was used to compare these alternative technologies with the commonly used unit ventilators that are ventilation-only systems, the finding was that the alternative technologies were superior.

Energy recovery ventilators (ERVs) were installed in two classrooms in two schools in Nevada (a hot, arid climate) to increase the ventilation rates (Shaughnessy et al. 1998). The ventilation rates of outdoor air prior to installation of the ERVs were only 1.4–4.4 cfm per occupant. The ERVs boosted the outdoor air ventilation rates in the classrooms to approximately 21 cfm per occupant. The $CO_2$ levels prior to installation of the ERV were consistently above 1000 ppm and occasionally exceeded 5000 ppm. In the classrooms, average $CO_2$ concentrations were reduced to below 1000 ppm with the ERVs operating. Concentrations of total VOCs averaged less with the ERVs operating, but were highly dependent on source and activity. Shaughnessy et al. found no correlations between the operation of the ERVs and bioaerosol levels and airborne particle concentrations. In the hot, arid climate, bioaerosol concentrations were very low both indoors and outdoors, and differences between the ventilation conditions were impossible to distinguish. A total energy balance on each of the ERV systems indicated a negative energy usage impact, probably as a result of to the climate. ❖

## 8 ❖ Impact of IAQ on Productivity and Satisfaction in the Learning Environment

Even though IAQ is perceived to be important for the learning ability of students (Daisey and Angell 1998), there have been few good scientific, statistically sound studies of school IAQ and its impact on the learning ability of students. Romm (1994) and Romm and Browning (1994) have documented that buildings and offices designed or renovated to reduce energy use and indoor pollution boosted worker efficiency by increasing output, decreasing errors, and improving attendance. Romm looked for a similar result in schools but found that there are virtually no environmentally sustainable schools and few studies on the productivity consequences of energy-saving measures in educational facilities. Lundin (1999b) found covariance among students' atopic sensitivities, IAQ, the physical environment, and the study environment. He suggests that the combination of a bad physical environment and a bady study situation may be a determining factor in symptom frequencies. McLoughlin et al. (1983) conducted a series of studies to clarify the relationship between allergies and school performance and behavior. Although he was not able to demonstrate a direct link between allergy and allergy treatment and academic performance, he was able to show that there was a relationship between respiratory problems and listening and attention. He found that eustachian tube disfunctions were related significantly to academic performance and behavior. There are also studies linking specific environmental conditions, such as light, noise, or room color, to student performance (Lytton 1997).

Subjective perception of impaired mental performance due to poor IAQ was reported by 21% of 627 Swedish secondary school pupils answering a postal questionnaire (Smedje, Norback, and Edling 1996). The subjective data was paired with exposure measurements in 28 classrooms. Reports of impaired performance were more common in schools with lower air exchange rates, higher relative humidities, and higher concentrations of respirable dust, formaldehyde, VOCs, and total bacteria or molds. A relationship was demonstrated between subjective reports of impaired mental performance, measured indoor air pollutants, and low air exchange rate.

In a study of elementary schools in a Canadian school district, Landrus and Axcel (1990) found that children with allergies were disproportionately in the below-average category of academic achievement. They found that for a group of 366 children identified by their teachers as having asthma, allergies, or environmental sensitivity, there was a significant association between clay, odorous markers, wallpaper paste, and sand or water centers and a higher frequency of symptoms. In this same study, 540 children *not* identified by their teachers as having asthma, allergies, or environmental sensitivity nevertheless had significant symptom associations with inks, clay, and odorous markers. While the frequency of symptom occurrence was linked to exposure to these materials, no causal relationships were determined.

These studies provide anecdotal evidence that healthful and well-lit schools may result in higher academic achievement. However, the complexity of measuring academic performance and understanding how it is achieved challenges claims of direct causal links.

Three different researchers studied the relationship between humidification and absenteeism (Sale 1972; Ritzel 1996; Green 1974, 1985). Sale and Ritzel studied controlled populations of kindergarteners to determine the relationship between respiratory illness and space relative humidity. In both studies, in the schools where the humidity was increased with humidifiers, absenteeism was 40–50% lower than in unhumidified schools. The schools reported a decrease in colds, sneezing, sore throats, and fever experienced by the children in spaces humidified in winter. Sale included approximately 500 kindergarten children in the study, investigating the impact of humidification in the home in conjunction with humidification in the school. The students were divided into four groups (the rate of absenteeism for each group is given in parentheses): humidification at home and at school (1.3%), humidification at school only (3.9%), humidification at home only (5.1%), and no humidification (7.1%).

Green compared the absenteeism in 18 schools, a total of about 4800 students, for 11 years. Part of the schools were humidified to greater than 25%, and others were not humidified. There was a statistically lower rate of absenteeism in the humidified schools. He concluded that a possible reason for the reduction in absenteeism may have been a reduction in disease transmission.

Fischer (1996) compared the actual cost premium associated with accommodating ASHRAE Standard 62-1989 recommendations in school facilities with the costs for

the same facility designed to provide only 5 cfm per student of outdoor air without controlling the indoor relative humidity to between 60 and 30%. This investigation concluded that cost premiums associated with compliance with ASHRAE 62-1989 recommendations ranged from $62 to $205 per student, and averaged $95 and $142 for the single-wheel total energy recovery system (TERS) and the dual-wheel desiccant-based total energy recovery system (DWERS) approaches, respectively (Table 6). Fischer concluded that the cost savings and cost avoidance associated with the benefits likely to be recognized from providing a desirable IAQ in the school environment would justify this additional expenditure.

Fischer also surveyed school operators to quantify legitimate cost savings and cost avoidance numbers (see Table 6) to support the conclusion that the payback period associated with providing a desirable IAQ may be very short. He reported that many of the benefits listed would be recognized year after year, whereas the cost associated with providing the desired IAQ is a one-time expense if energy recovery is used to offset the added energy requirements. The projected benefits—which included reductions in absenteeism, substitute teachers, and health care costs—quickly exceed the initial expense associated with the improved indoor environment.

Hardin, in personal communication, estimates the cost to the state of Washington for poor humidity control in schools in billions of dollars for structural damage alone. Schools are not the only structures with billions of dollars with structural damage due to poor humidity control in Washington State. Hardin also estimates that there are billions of dollars of damage to multifamily housing.

The U.S. Environmental Protection Agency in partnership with NAESCO (a trade association representing energy service companies) has demonstrated the integration of IAQ improvements and energy efficiency upgrades to schools using "performance contracts" (Redding and Harrison 1999). Using this approach schools can finance capital upgrades, which improve IAQ by upgrading schools HVAC systems to meet the ventilation recommendations of ASHRAE Standard 62-1989, through contracts that are repaid from the utility and maintenance savings realized as a result of new equipment, systems, and controls. Redding and Harrison estimate, based on a five-school demonstration project, that the energy savings will average 407,200 kWh per school and that costs will average $535,300 per school.

**Table 6. Cost vs benefit comparison for providing desirable IAQ in schools**

| Added costs for desirable IAQ | Benefits from maintaining desirable IAQ | |
|---|---|---|
| **Case 1:** Hot, humid climate[a]<br>DWERS approach: $142/student[b]<br><br>**Case 2:** Moderately humid/cold climate[c]<br>TERS approach: $95/student[b] | • **Improved effectiveness of the learning process**<br>Impacts on comprehension, alertness, drowsiness, allergies, respiratory illness | Significant $/ student |
| **Notes**<br><br>*Abbreviations:*<br>DWERS = dual-wheel desiccant-based total energy recovery system<br>TERS = single-wheel total energy recovery system<br><br>[a] Assumes the use of the dual-wheel, total energy recovery preconditioner directly to and from each occupied area, decoupling the outdoor air load from space load, which is handled by a typically 2-ton conventional HVAC.<br><br>[b] Added cost reflects increase in overall mechanical cost of either the DWERS or TERS approach providing 15 cfm/person of outdoor air (as compared with only 5 cfm/person with a conventional HVAC) and continuously controlling space relative humidity.<br><br>[c] Assumes the use of a single-wheel energy recovery preconditioner ducted to space or to the return air side of a conventional HVAC unit. | • **Reduced absenteeism**<br>Funding increase based on reduced absenteeism | $57/student/year |
| | Savings due to fewer substitute teachers | $5/student/year |
| | Health care savings, reduced doctor visits | $107/student/year |
| | • **Avoided property damage**<br>Carpet replacement in a typical school | $37/student |
| | Ceiling tile replacement in a typical school | $22/student |
| | Partial book replacement | $3/student |
| | • **Reduced maintenance costs**<br>Doubled time between filter changes | $5/student/year |
| | • **Avoided remediation**<br>Avoided duct cleaning, facility IAQ investigation, legal expenses | Significant $/ student |

There are few reported estimates of the magnitude of productivity gains in schools from improved IAQ, but there are a few estimates on the productivity gains in the total building stock in the United States (Fisk and Rosenfeld 1997). Based on these data, Fisk and Rosenfeld estimate that the United States can achieve potential annual savings and productivity gains of $6–$19 billion from reduced respiratory disease, $1–$4 billion from reduced allergies and asthma, $10–$20 billion from reduced SBS symptoms, and $12–$125 billion from direct improvements in worker performance that are unrelated to health. They calculate that the potential financial benefits of improving U.S. indoor environments exceed costs by a factor of 18 to 47. These estimates justify changes in building code components pertinent to indoor air, such as prescribed minimum ventilation rates and minimum air filtration system efficiencies; in school, company, and institutional policies related to building and school design; in operation and maintenance practices; and in staff selection and training. ❖

## 9 ❖ CONCLUSIONS

This investigation makes clear that more research is justified to investigate the specific causes of IAQ problems within schools and to quantify the specific benefits that are recognized from providing a desirable indoor air environment. Given that the General Accounting Office concluded that one in five schools has IAQ problems, and given that thousands of schools are slated for construction or renovation within the next 5 years, the need to identify simple, effective, energy-efficient ways of resolving these IAQ problems is both obvious and significant.

Fortunately, as shown by this investigation, much credible research has already been conducted. Based on these scientific data, it can be concluded that most IAQ problems can be avoided (or resolved) by providing an adequate amount of outdoor air on a continuous basis, controlling space relative humidity so that it seldom exceeds approximately 60% or drops below approximately 30%, and using a level of outdoor air filtration efficiency necessary to prohibit most mold spores and fungi from entering the HVAC system.

The research conducted to date confirms that both proper outdoor air ventilation and humidity control are necessary. Too often in practice, one is obtained at the expense of the other. Packaged systems that provide the outdoor air volume only when the coil is energized improve humidity control but allow indoor contaminants to build to unacceptable levels. The same equipment can be operated with the supply fan running continuously and with an outdoor air damper adjusted to provide the required

*One in five schools has IAQ problems, and thousands of schools will be built in the next 5 years. How can we resolve these problems in existing schools and prevent them in new ones?*

*Most IAQ problems can be avoided or resolved by*

- *providing an adequate amount of outdoor air on a continuous basis,*
- *controlling space relative humidity so that it seldom exceeds approximately 60% or drops below approximately 30%, and*
- *using a level of outdoor air filtration efficiency necessary to prohibit most mold spores and fungi from entering the HVAC system.*

quantity of outdoor air, but humidity control is lost, especially at part-load conditions. Fortunately, proven and cost-effective system solutions exist that allow satisfaction of both the continuous ventilation and the humidity control objectives while they provide a central location for effective outdoor air filtration, which can be easily accessed for routine maintenance.

In summary, the research identified as part of this investigation provides the basis for the formation of a simple hypothesis: Most IAQ problems in school facilities can be avoided by (1) providing adequate outdoor air ventilation on a continuous basis (15 cfm per student), (2) controlling the space relative humidity between 30 and 60% and (3) providing effective particulate filtration of the outdoor air.

It is recommended that a research project be initiated to analyze a statistically significant number of existing school facilities, comparing those constructed with conventional HVAC system approaches that do not provide simultaneous, continuous ventilation and humidity control, with schools designed to include systems that meet the ventilation, humidity control, and filtration criteria in the previous paragraph. If our stated hypothesis is correct, the analysis we recommend should show very acceptable IAQ at the schools designed and operated to conform to ASHRAE Standard 62-1989 recommendations, and very few IAQ complaints by the occupants. Conversely, the schools that do not conform to the ASHRAE IAQ standard should show much higher levels of indoor air contamination and microbial activity and a much higher level of dissatisfaction with regard to IAQ among the occupants.

If the recommended research is completed, and assuming the stated hypothesis is confirmed, valuable direction would be provided to school officials, architects, and consulting engineers responsible for schools scheduled for construction or renovation in the future, as well as those faced with resolving the many IAQ problems that currently exist in school facilities. ❖

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